REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION
Unclassified

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT

4. PERFORMING ORGANIZATION REPORT NUMBER(S)
BRL-MR-3684

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION
US Army Ballistic Rsch Lab

6b. OFFICE SYMBOL (If applicable)
SLCBR-IB-B

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS (City, State, and ZIP Code)
Aberdeen Proving Ground, MD 21005-5066

7b. ADDRESS (City, State, and ZIP Code)

8a. NAME OF FUNDING / SPONSORING ORGANIZATION

8b. OFFICE SYMBOL (If applicable)

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS (City, State, and ZIP Code)

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
FACILITY FOR VISUALIZATION OF LIQUID PROPELLANT SPRAY COMBUSTION AT HIGH PRESSURES

12. PERSONAL AUTHOR(S)
Avi Birk and Phil Reeves

13a. TYPE OF REPORT
MR

13b. TIME COVERED
FROM ________ TO ________

14. DATE OF REPORT (Year, Month, Day)

15. PAGE COUNT

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

An injector-combustor assembly and a dedicated flow system, currently under construction, are described which allow the photography and spectroscopy of liquid propellant spray combustion in high pressure and temperature clear inert gas environments. The gas is pressure regulated from a room temperature reservoir and is heated convectively in a particle bed heater prior to entering a windowed chamber (combustor). The unique particle bed has a heat capacity of 0.67 cal/cm^{3}C and up to 2 KW/cm^3 power density for gas heating. Typically, steady state gas flow pressure and temperature are obtained in the combustor after 1 sec for a duration of 4 sec with downward velocities of less than 1 m/sec and temperatures ranging from 400 C to 800 C for pressures of 10 MPa to 69 MPa. The patented injector is mounted at the bottom of the combustor and is capable of

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
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21. ABSTRACT SECURITY CLASSIFICATION
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22c. OFFICE SYMBOL
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19. ABSTRACT (CON'T)

injecting liquid propellants at upward velocities reaching 300 m/sec for both solid core circular jets and annular jets. The data from preliminary test of a lower pressure abridged system bode well for the complete high pressure system.

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MEMORANDUM REPORT BRL-MR-3684

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FACILITY FOR VISUALIZATION OF LIQUID PROPELLANT SPRAY COMBUSTION AT HIGH PRESSURES

by AVI BIRK
PHIL REEVES

JULY 1988

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U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
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I. INTRODUCTION

The combustion of liquid propellants (LP) in gun environment occurs at pressures above 10 MPa. To aid the engineers in scaling up present gun combustion chambers for larger and higher performance guns it is beneficial to establish the following: a) breakup and penetration distances of thick jets (round solid, or annular) in high density gas, b) ignition delays and combustion times, and c) type of combustion (e.g., whether supercritical). The information gained may also aid in designs to avoid combustion instabilities. Also, modelers can benefit from more relevant test data. The current knowledge of LP jet breakup and combustion in gun chambers is speculative. Low pressure spray tests or strand burner tests (even at high pressures) have only limited utility. Clearly, tests have to be conducted with sprays at high pressures in a facility which will enable visualization of sprays. Visualization entails diverse means of detection such as cinematography, spectroscopy, and particle sizing by optical techniques.

Facilities to test spray combustion at pressures above 10 MPa are virtually nonexistent. Only a few facilities, allowing good visualization, exist for lower pressures. The closed circuit tunnel of Ref. 1 (4.5 MPa, 400 C for diesel sprays) is a distinct example. In that tunnel clear inert gas is used. Such a system, however, cannot be engineered for the temperatures and pressures of interest in LP sprays. High pressure and temperature can be achieved rather easily by igniting a combustible mixture of gases such as oxygen, hydrogen and a diluent gas (e.g., Ref. 2). However, the test times are short (less than 50 msec); there is the risk of detonation in larger chambers; and most importantly, above 10 MPa, the high temperature of the gas results in intense radiation from the flame and various contaminants in the chamber. Such radiation prevents any visualization. (In actual gun chambers this problem is exacerbated). Water condensation on the windows (present in most flames) is another drawback. For high pressures, a facility employing nonvitiated clear gas is required. Such a facility has been conceived with the following specifications:

1. Optically clear large rectangular windows (4 in x 1.4 in) to allow for compactness and yet allow a long stretch of spray view.

2. Provide nonvitiated gas at 800 C, 69 MPa; pressures and temperatures well above the supercritical values for water which is a major constituent of the LP's.

3. Long test time (4 sec) for proper data collection.

In addition, a variable geometry injector for LP injection has been designed with the following features:

1. Injection velocities to 300 m/sec (gun velocities).

2. Annular (gun geometries) as well as solid round jets up to 3 mm thick.

3. Fast response times (msec-gun times).

The various components of the facility are currently under construction. Some components have been assembled into a lower pressure abridged system and underwent performance tests. The facility and, in particular, its most unique components are described next. Also described are the performance tests with the abridged system.

II. FACILITY DESCRIPTION

The outline of the facility is shown in Figure 1. It is an open loop flow system. The mode of operation is as follows. Room temperature inert gas is stored in a high pressure gas reservoir (138 MPa, 10,000 cc). Meanwhile, a particle bed heater is heated up electrically at atmospheric pressure. The bed, which is encased in a high pressure vessel, consists of submillimeter ceramic particles packed between two coaxial concentric porous frits. The bed stores a large amount of heat which can be extracted rapidly due to the large combined surface area of the particles. When the bed reaches the desired temperature, the test can be started by dumping gas from the reservoir through the bed and into the test chamber. A dome pressure regulator regulates the pressure. The duration of the test is determined by means of the pneumatically controlled ball valve downstream of the regulator. There is only a small pressure drop through the bed and with the proper gas, the gas attains the bed temperature. For a more complete discussion of the properties of high pressure particle beds, the reader is referred to Reference 3. The transmission line between the bed and the test chamber is kept hot by means of a cylindrical radiation oven. In this manner heat losses are minimized. The inlet of the chamber is nozzle shaped and the outlet flow of gas is controlled by an orifice downstream of the chamber. The gas is cooled to room temperature prior to exiting through the orifice. This allows for a constant and predetermined gas mass flow rate through the system. A steady low velocity flow of gas is established in the chamber. The temperature and pressure in the chamber are measured by a fast response thermocouple and a fast response pressure transducer. The flow of gas in the chamber results in uniform temperature throughout the chamber. In the absence of gas flow, heat losses to the walls and free convective eddies would shorten test time to less than half a second. When steady state conditions are achieved LP injection is initiated. The particle bed and injector are described next in more detail.

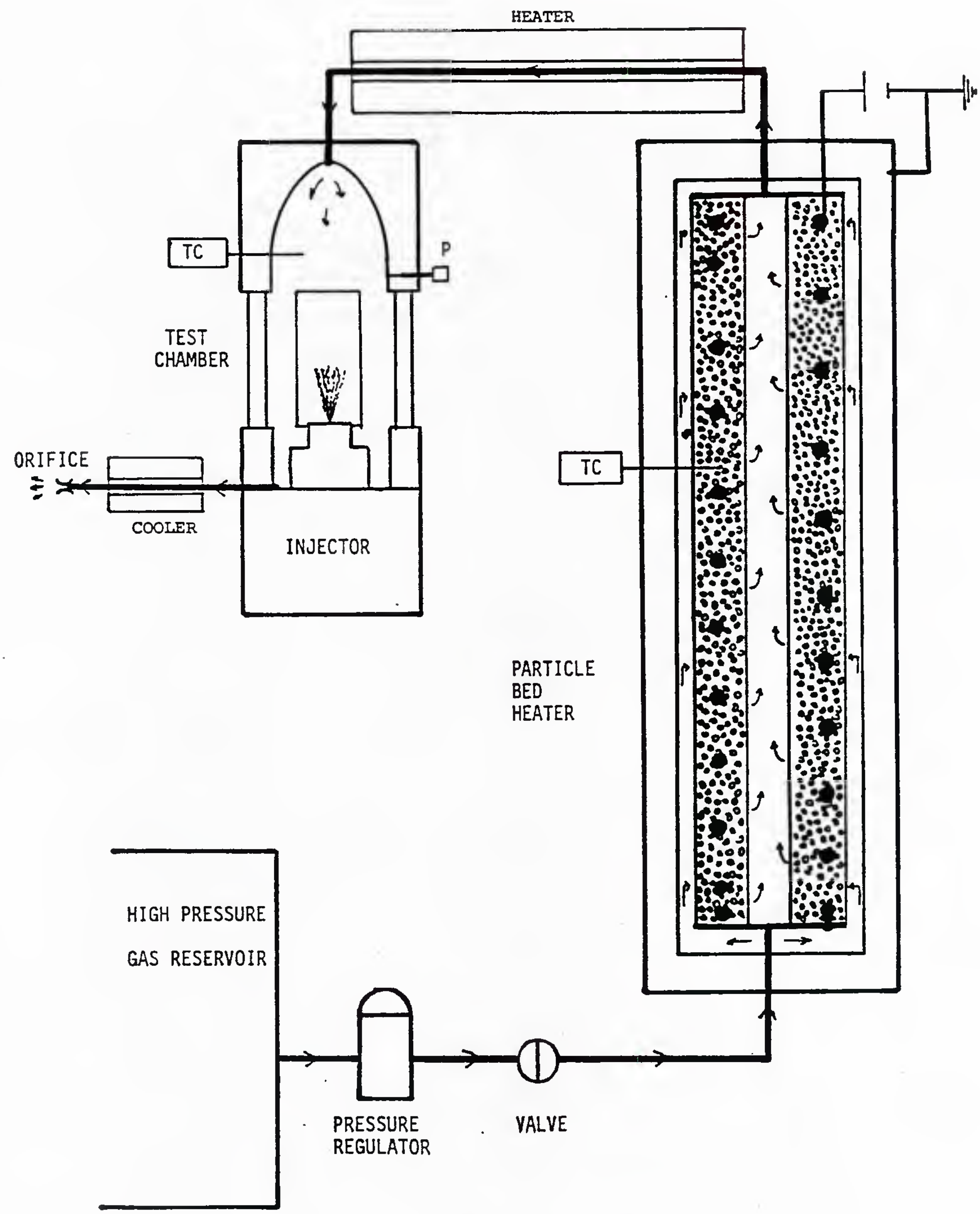

Figure 1. Facility Outline

1. PARTICLE BED

The particle bed is illustrated and shown to scale in Figure 2. It was designed and fabricated under contract at Brookhaven National Laboratory. The pressure vessel is a standard Autoclave vessel. The bed is suspended from the vessel's plug. This allows for thermal expansion. The bed is insulated from the chamber walls by a gas gap. Heat losses from the bed are due to conduction to the plug, and radiation and free convection to the walls. The bed is heated to 1000 C

while the pressure vessel walls are kept below 315 C (by free convection to its surroundings). The gas enters at the bottom and exits through a passage drilled through the plug. The vessel volume is 2000 cc while the volume of the bed is 1000 cc; most of the latter is taken up by 900 micron diameter spherical alumina particles. The frits are made from stainless steel with 20 and 40 micron porosities of the outer and inner frits respectively. Power consumption of the bed is typically 1.5 KW at 50 amperes. The heating element is a braided Kanthal coil. The bed stores 666 Kcal at 1000 C and can deliver 2 KW/cc. For example, 1000 cc nitrogen at 69 MPa (to fill the test chamber) can be heated up to 1000 C (50 Kcal) in 100 msec. The bed is currently undergoing testing to establish its actual performance. It has already been determined that it needs refinements.

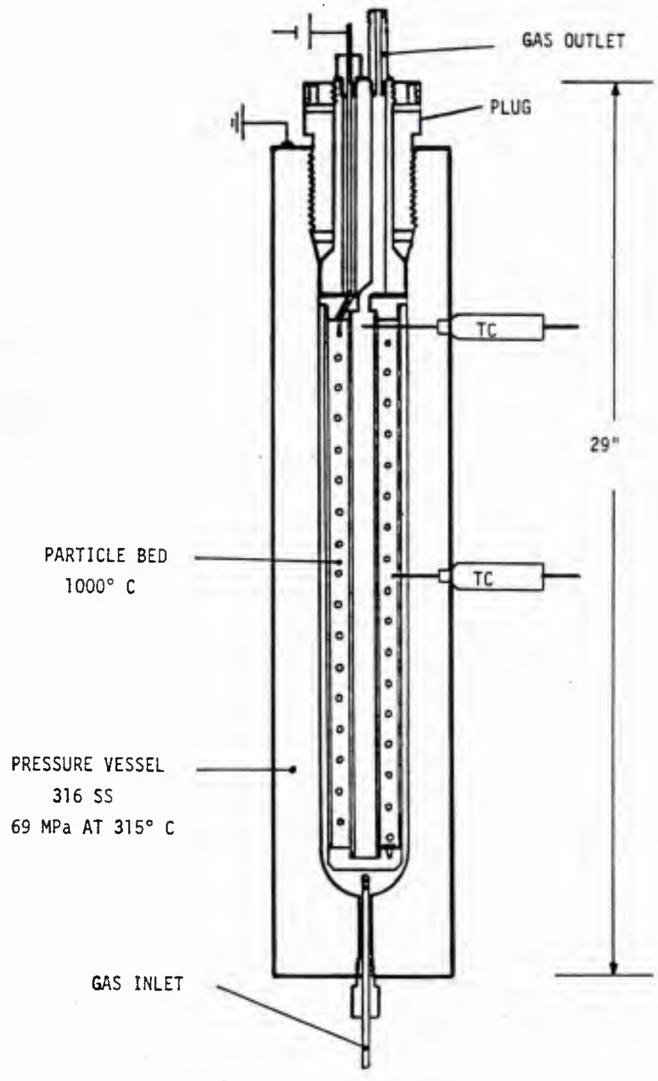

Figure 2. Particle Bed Heater

2. INJECTOR

A patented injector has been developed and fabricated. It is illustrated in Figure 3. The injector's injection port is variable; annular geometries as well as round orifices can be used. It can inject liquid at pressures approaching 138 MPa and it has 138 cc liquid capacity. It can be activated solely by the pressure of the gas in the test chamber or by auxiliary gas. The injection arresting gas prevents the piston from retreating under the test chamber pressure and injecting the liquid. The stem valve, besides preventing injection, also protects the LP from the hot chamber gas above it. When the arresting gas is discharged, the stem valve retreats thus opening the injection port. Just as in the regenerative liquid propellant gun, the differential areas of the retreating piston result promptly in high injection pressure. The injection pressure can be further augmented by spacing injection augmentation gas between the control rod base and the piston. The pressure is measured via transmission rod and fluid. The annular injection port configuration is intended to be used mostly with inert liquid as the liquid in the injector is exposed to the hot gas and may ignite prematurely before injection. The injector still awaits testing.

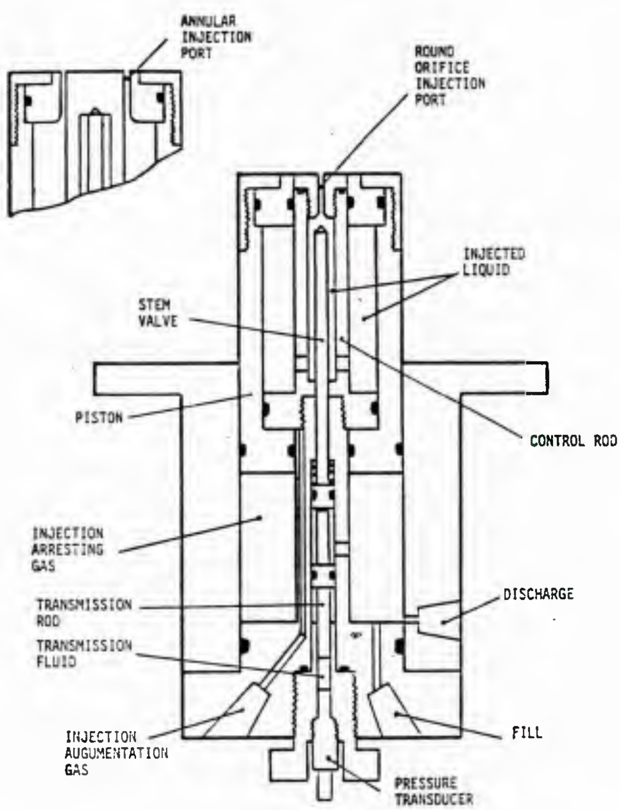

Figure 3. Injector Layout

III. OPERATING CONSIDERATIONS

The operating considerations discussed here will relate to the heat losses in the transmission line and test chamber and to the choices of gas. The heat transfer processes in the particle bed and its pressure vessel are too complex to be discussed here.

1. THERMAL EFFICIENCY

As mentioned, the flow of gas is controlled by an orifice downstream of the test chamber. The mass flow rate is:

$$\dot{M} \approx C_1 P A_t (\bar{M}\gamma)^{1/2} \tag{1}$$

The gas temperature does not appear in Equation 1 because the gas is cooled to room temperature prior to passing through the orifice.

The thermal energy carried by the gas is:

$$\dot{Q}_F = \dot{M} C_p T \tag{2}$$

The heat loss to walls (for cylindrical geometries) is:

$$\dot{Q}_L \approx C_2 Re^m \frac{K}{D} A \Delta T; \quad m = 0.5 \text{ to } 0.8 \tag{3}$$

Equation 3 is a general form for heat transfer and omits the Prandtl number which is virtually constant and the same for most gases. The exponent m will tend to be close to 0.8 for the turbulent flow of our case. Writing Re in terms of $\dot{M}$ one obtains:

$$\dot{Q}_L \approx C_3 K L \Delta T \left(\frac{\dot{M}}{\mu D}\right)^m \tag{4}$$

As evidenced from Equation 4, in order to keep heat losses low, one needs to design short transmission lines with large diameters. Preheating the transmission line to decrease ΔT is highly beneficial.

Higher chamber gas temperatures are achieved when $\dot{Q}_L/\dot{Q}_F$ is minimized. From Equations 1, 2 and 4 we obtain:

$$\frac{\dot{Q}_L}{\dot{Q}_F} \approx C_4 L \frac{\Delta T}{T} \frac{\mu^{1-m}}{D^m (PA_t)^{1-m} (\bar{M}\gamma)^{(1-m)/2}} \tag{5}$$

As Equation 5 demonstrates, higher efficiency (higher gas temperature) is obtained at higher pressures, higher mass flow rates, and denser gas.

2. CHOICE OF GAS

In order not to burn the high temperature stainless steel frits of the bed, the current system is limited to inert gases. Two obvious choices are nitrogen and helium. Helium has lower volumetric heat capacity than nitrogen. It is much lighter and has higher heat conductivity and diffusivity. These qualitative differences between helium and nitrogen affect the overall performance of the facility. The effects are summarized in the following table. The * in Table 1 denotes advantageous effect.

TABLE 1. Choice of Gas

	Nitrogen	Helium
Volumetric Heat Capacity		* Less
Heat Loss	* Less	
Jet Breakup	* Better	
Spray Heatup		* Faster
Visual Clarity		* Better
Sealability	* Easier	
Cost	* Cheaper	

In conclusion, there is no clear cut advantage to either nitrogen or helium. To simulate the high densities of gun environments for jet breakup tests, nitrogen is the choice due to its high density.

IV. PRELIMINARY TESTS

As only the particle bed heater was completed on time, a lower pressure system had been tested to affirm the operational principle of the facility. In particular, the test chamber and injector (modified) used in Reference 2, were used again. A 14.3 mm diameter (9/16 inch) tube, 30 cm long, heated to approximately 300 C was used as a transmission line. Both helium and nitrogen gases were employed. The first series of tests are depicted in Figures 4 to 6. As can be seen from Figure 4, steady state conditions are achieved after 1 second. In tests with helium, steady conditions were achieved after 0.3 seconds (because the chamber fills faster with the higher sonic velocity

helium). The temperature peaks well before the pressure (Figure 4). A complex turbulent convective heat transfer mechanism is involved. Theoretically, with the absence of heat losses, a temperature $\gamma * T_{bed}$ can be obtained. The thermocouples used had a millisecond response time. Despite the disparate locations of the thermocouples, their readings almost overlap. This was achieved only when low velocity gas flow was established in the chamber on the order shown in Figure 5. The velocities in Figure 5 are estimated based on A_t (larger A_t results in higher V) and the measured chamber pressure and temperature. Higher pressure resulted in higher temperature as is evident from Figure 6. Both Figures 5 and 6 conform with the trend predicted by Equation 5 regarding the thermal efficiency. Tests with helium revealed similar trends.

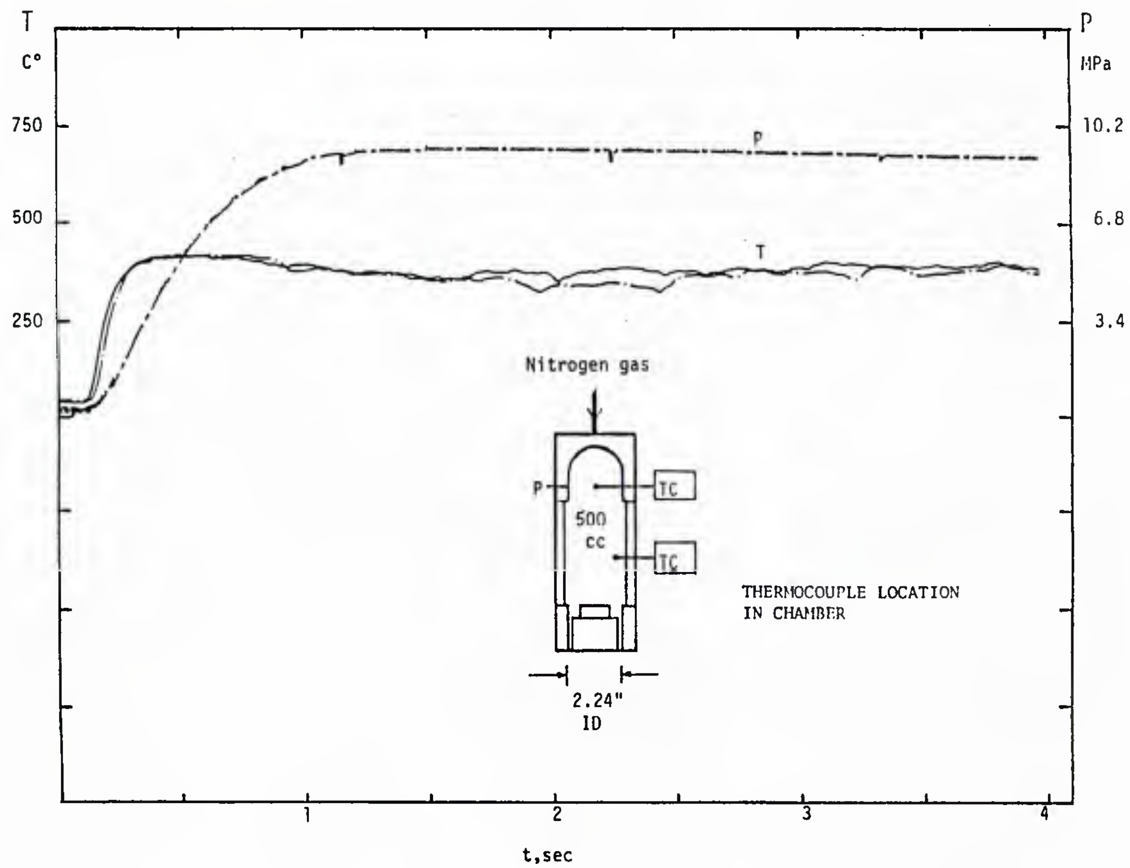

Figure 4. <u>The Temperatures in the Chamber Are Rather Uniform</u>

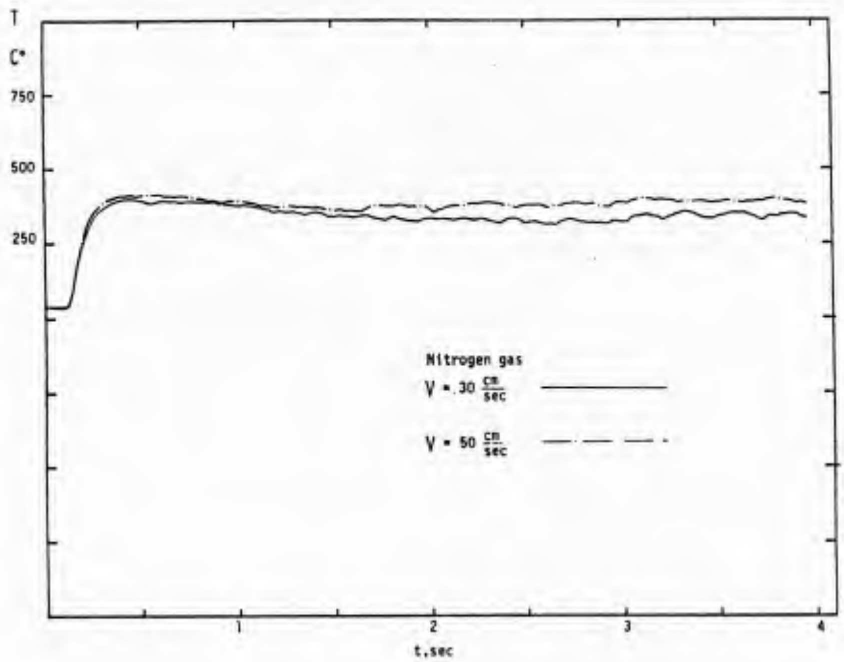

Figure 5. <u>Higher Chamber Gas Velocities Result in Higher Temperatures</u>

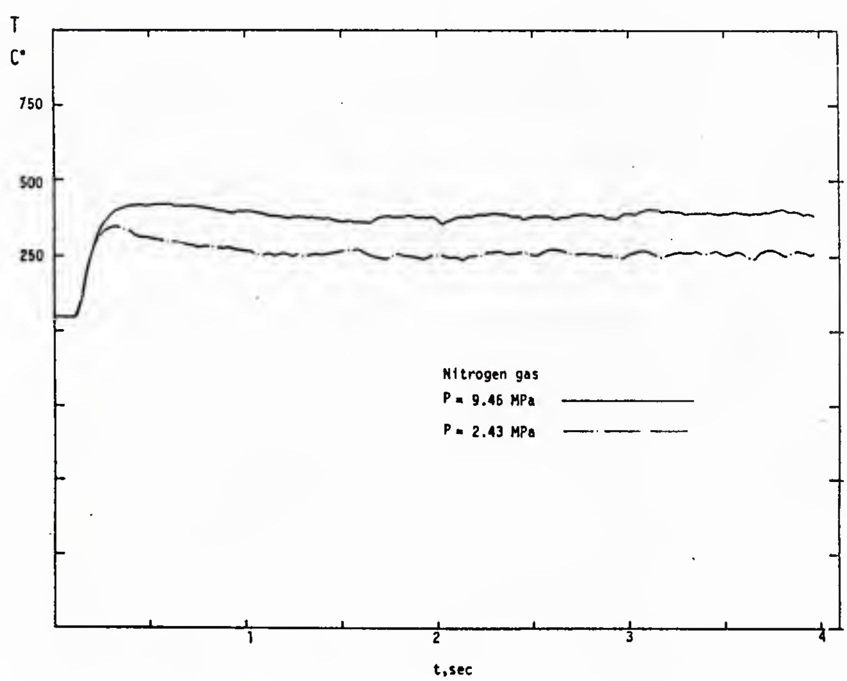

Figure 6. <u>Higher Chamber Pressures Result in Higher Temperatures</u>

To find out whether the conditions depicted in Figures 4 and 5 are already sufficient for LP ignition, LGP 1846 was injected into both helium and nitrogen at 9.5 MPa and 400 C. The jets were injected from a 1 mm diameter round orifice with 76 m/sec velocity for 50 msec duration. High speed cinematography revealed that in both cases, ignition and transition to flame were observed after approximately 20 msec delay. These results are very encouraging considering the propensity of LP's to ignite and burn promptly at higher pressures.

In the future, as the facility becomes fully operational, spray tests will be extended to 69 MPa. Various diagnostics methods are intended for use. In particular: a) high speed cinematography with copper vapor laser strobing, b) holography, c) two dimensional spectroscopy, and d) particle sizing (for dilute sprays).

V. CONCLUSIONS

1. A compact facility to research LP sprays in a 10 to 69 MPa, 400 to 800 C (estimated) nonvitiated gas environment is feasible.

   In addition:

   A. The gas environment can be established in less than 1 second.

   B. Uniform temperatures are sustained by allowing the gas to flow at less than 50 cm/sec.

2. Preliminary experiments indicate better performance at the higher pressures.

3. Based on the tests, the gas temperatures obtained in the facility are sufficient for LP jet ignition, thus enabling spray combustion research.

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NOMENCLATURE

A - Area

A_t - Orifice area

C_1 - Dimensional constants appearing in Eqs. 1, 3, 4, and 5

C_2

C_3

C_4

C_p - Specific heat

D - Diameter

K - Thermal conductivity

L - Length

$\dot{M}$ - Mass flow rate

$\bar{M}$ - Molecular weight

P - Pressure in chamber

$\dot{Q}_F$ - Rate of thermal energy flow

$\dot{Q}_L$ - Rate of heat loss

Re - Reynolds number

t - time

T - Chamber temperature

V - Chamber gas velocity

ΔT - Difference between wall and gas temperatures

γ - Specific heat ratio

μ - Viscosity

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